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SIMULATION STUDY OF THREE INSTRUMENT DISPLAYS TO ASSIST IN AIRPLANE THRUST MANAGEMENT

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16. Abstract

Three displays were evaluated on a piloted simulator, each of which provided information which could be used in thrust management. The three displays were (1) rate of change of speed, (2) potential flight-path angle, and (3) potential rate of climb. Results are presented in the form of time histories, histograms, and pilot comments. The results include comparisons of flight-path and speed control and throttle activity with and without each display and pilot comments.

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SIMULATION STUDY OF THREE INSTRUMENT DISPLAYS TO ASSIST IN AIRPLANE THRUST MANAGEMENT

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SUMMARY

Three displays, each of which provided information to be used in thrust management of an airplane, were evaluated. These three displays were (1) rate of change of speed, (2) potential flight-path angle, and (3) potential rate of climb. The evaluation utilized a piloted fixed-base aircraft simulator. Pilots used in the evaluation included three NASA test pilots, two airline captains, and an aeronautical engineer with piloting experience in light planes and in simulators. The tests consisted of making changes in flight conditions which involved making major changes in thrust. Two subsonic flight conditions and one supersonic flight condition were selected. Tests were made with each of the thrust-management displays and were repeated with conventional instrumentation without using any of the thrust-management displays.

The results are presented in the form of time histories of tests, histograms of throttle motions, and pilot comments. The results show that, on the average, about one-half the number of throttle motions per minute of test occurred for tests with either the potential-flight-path-angle or potential-rate-of-climb display when compared with tests without a thrust-management display. Also, on the average, a slightly higher number of throttle motions per minute of test occurred for tests with the rate-of-change-of-velocity display as compared with tests without a thrust-management display. The pilots commented that, in general, the use of a thrust-management instrument reduced the pilot's mental workload by providing a fairly quick and accurate method for setting thrust for any flight conditions but that the pilot's scan pattern workload was increased.

INTRODUCTION

The thrust for a particular flight condition, in the operation of a jet airplane, requires a specific engine pressure ratio. These engine pressure ratios are obtained by throttle settings. The pilot becomes familiar with many of these throttle settings through repeated use. Often, however, during operation of the airplane, the pilot is required to seek other than the familiar settings due to variations in operating environment and deviations from planned operating conditions. When this occurs, the pilot must resort to a cut-and-try method for the setting of throttles to obtain trimmed thrust. With the increase in the operating environmental range of newer jet airplanes, there are more operating conditions. This fact, coupled with the larger size and complexity of the proposed airplane, tend to increase the pilot's difficulities in setting the correct thrust for the conditions at hand (ref. 1).

A partial solution to the problem is to provide the pilot with information for assistance in thrust management.

In the present tests, displays of each of three quantities which are related to thrust management were evaluated: (1) rate of change of speed, (2) potential flight-path angle, and (3) potential rate of climb. The evaluation utilized a piloted fixed-base aircraft simulator. The tests consisted of initially trimmed level flight and then establishing trimmed climbs or descents followed by a return to trimmed level flight. A selected speed was to be held for each test. Tests were made both with and without the thrust-management instruments. Results are presented as time histories, histograms, and pilot comments.

SYMBOLS

a	speed of sound, feet per second (meters per second)
a_{fp}	acceleration along the flight path as measured by an accelerometer, feet per second^2 (meters per second^2)
$C_{D_{C_L^2}}$	trimmed drag due to lift factor
$C_{D,o}$	drag coefficient for zero lift coefficient
C_L	lift coefficient
D	drag, pounds (newtons)
g	acceleration due to gravity, feet per second^2 (meters per second^2)
h	altitude, feet (kilometers)
$\dot{h}$	rate of change of altitude, feet per minute (meters per minute)
$\dot{h}_p$	potential rate of change of altitude, feet per minute (meters per minute)

K	change in speed per flight-path angle, $\frac{\dot{V}}{g\gamma}$
k	ratio of specific heats
L	lift, pounds (newtons)
M	Mach number
n_z	acceleration normal to flight path, g units
P	period, seconds
p	static pressure, pounds per foot^2 (newtons per meter^2)
q	dynamic pressure, pounds per foot^2 (newtons per meter^2)
q_c	impact pressure, pounds per foot^2 (newtons per meter^2)
R	perfect gas constant, feet per second-$^{\circ}$F (meters per second-$^{\circ}$K)
S	wing area, feet^2 (meters^2)
T	thrust (assumed parallel to body axis), pounds (newtons); also absolute temperature in appendix B and figure 14, $^{\circ}$F ($^{\circ}$K)
t	time, minutes
$t_{1/2}$	time to one-half amplitude, seconds
V	speed, feet per second (meters per second)
$\dot{V}$	rate of change of speed, knots per minute or feet per second^2 (meters per second^2)
$\dot{V}_i$	rate of change of indicated airspeed, knots per minute
W	weight, pounds (newtons)
α	angle of attack, degrees or radians

γ flight-path angle, degrees or radians

γ_p potential flight-path angle, degrees or radians

θ aircraft pitch angle, degrees or radians

ρ density, slugs per foot^3 (kilograms per meter^3)

ϕ bank angle, degrees

METHOD AND EQUIPMENT

Airplane Simulator

The thrust-management displays were evaluated on a fixed-base aircraft simulator. The simulator consisted of a current jet transport cockpit which was connected to analog computers. Six-degree-of-freedom equations of motion representing the airplane were programed on the computers. The pilot inputs consisted of control and throttle motions. Computer outputs, defining airplane attitudes and velocities, were displayed to the pilot on modern airplane-type instrumentation.

Airplane Characteristics

The airplane simulated was a variable-geometry supersonic transport design. Airplane parameters were programed as functions of sweep angle and Mach number. Engine thrust was programed as a function of density, Mach number, and throttle position. Some basic and augmented longitudinal aerodynamic, control, and performance characteristics are presented in table I for two center-of-gravity locations and for the subsonic and supersonic conditions which approximated the conditions of the tests. Augmentation consisted chiefly of an increase in pitch damping. Most of the tests were made at the forward center-of-gravity condition with augmentation.

Instruments

General description of pilot panel instruments.- The pilot's primary flight instruments and a thrust-management instrument are shown in figure 1. The thrust-management instrument is shown in the location which was used for the testing of each of the three types of thrust-management displays. The slow-fast indicator was used to present one of the thrust-management displays for a portion of the tests. General information concerning the flight instruments shown in figure 1 is presented in table II.

Thrust-management instruments.- The three thrust-management instruments tested – (1) rate of change of speed $\dot{V}$, (2) potential flight-path angle γ_p, and (3) potential rate of climb $\dot{h}_p$ – are shown in figure 2. A general description of the thrust-management instruments is presented in table III.

$\dot{V}$ thrust-management instrument: The rate-of-change-of-speed $(\dot{V})$ thrust-management instrument was a single-movement instrument. Several ranges of rates of change of speed were investigated, and these are listed as configurations A, B, and C in table III. The rate of change of speed is presented in knots per minute. The movement was nonlinear such that a larger movement of the pointer occurred for the lower values of rate of change of speed. The black shield on the right side of the instrument face beyond the maximum scale markings allowed the white pointer tip to be hidden from view during runs in which the thrust-management instrument was not being used. The $\dot{V}$ thrust-management display was flown as a null-type meter which meant that the pilot tried to keep the pointer at zero. The pilot used conventional airplane instrumentation to establish the flight path. The $\dot{V}$ thrust-management display was used to establish thrust for control of airspeed. A null or zero reading meant that the aircraft was not changing speed along the flight path. A setting greater than zero meant that the aircraft was accelerating along the flight path, and a setting less than zero meant that the aircraft was decelerating.

γ_p thrust-management instrument: The potential-flight-path-angle (γ_p) thrust-management instrument was a two-movement instrument having a pointer and index. The potential flight-path angle was displayed on the index, and the airplane flight-path angle was displayed on the pointer. The instrument was calibrated in degrees. The flight-path-angle instrument also contained a black shield on the right side of the dial face. The index was hidden behind the shield during tests in which the instrument was not being used as a thrust-management instrument. The movement of the index was primarily controlled by use of the throttles. A zero reading on the index meant that the throttles had the correct setting for trimmed thrust in level flight. Forward throttle displacement from the trimmed position resulted in a potential climb angle reading of the index. Rearward throttle displacement from the trimmed position resulted in a potential descent angle reading of the index. When the index and the pointer were matched, then the airplane was thrust trimmed for constant-speed flight on the existing flight path. If the pointer was above or below the index, then the airplane was respectively slowing or gaining in speed.

$\dot{h}_p$ thrust-management instrument: The potential-rate-of-climb $(\dot{h}_p)$ thrust-management instrument was the same type of two-movement instrument as the γ_p thrust-management instrument. Potential rate of climb was displayed on the index, and the airplane rate of climb was displayed on the pointer. The instrument was calibrated in thousands of feet per minute (km/min). The index was hidden behind a black shield on the instrument face during tests in which the instrument was being used an an ordinary rate of climb meter. The $\dot{h}_p$ display was employed for thrust management in the same manner as that described for the γ_p display.

Thrust-management display signals: The basic signal used for the three thrust-management displays was obtained from a mathematical model of an accelerometer alined with the flight path (ref. 2). The accelerometer was assumed to be servo-driven in alinement with the flight path by means of an angle-of-attack vane (which measures the angle between the airplane axis and the relative wind axis). The basic relationships of the accelerometer signal to the displayed quantities $\dot{V}$, γ_p, and $\dot{h}_p$ for straight flight are derived in appendix A and are as follows:

$$\dot{V} = g\left(\frac{a_{fp}}{g} - \gamma\right)$$

$$\gamma_p = \frac{a_{fp}}{g}$$

where $\gamma_p = \gamma$ for $\dot{V} = 0$ and

$$\dot{h}_p = \frac{a_{fp}V}{g}$$

where $\dot{h}_p = \dot{h}$ for $\dot{V} = 0$. As can be seen in the first equation, the display of $\dot{V}$ also required the measurement of flight-path angle γ which was assumed available from a pitch attitude gyro measurement and the angle-of-attack-vane measurement ($\gamma = \theta - \alpha$).

The $\dot{V}$, γ_p, and $\dot{h}_p$ displays each give sufficient information to allow the pilot to thrust trim the airplane. A $\dot{V}$ display using a flight-path accelerometer signal was used with good results in thrust trimming several high performance jet airplanes (ref. 3). In initial tests on the simulator, the pilots also reported good results when using each of the displays to thrust trim the airplane. However, the pilots were annoyed by the motion of the display pointer and particularly by the motion of the index in response to fore and aft motion of the longitudinal control column. These motions on the index were caused by induced drag effects resulting from accelerated flight. As the pilots had demonstrated a tendency toward overcontrol (excessive fore and aft motion of the control column) at times in these tests, the flight-path accelerometer signal was compensated to try to remove these short period motion effects from the index. The compensation signal was derived in appendix A as equation (A15) as the magnitude of induced drag per incremental acceleration from 1g flight. The negative of equation (A15), $2C_{D_{C_L^2}} C_L(n_z - 1)$, is added to the flight-path-angle signal to remove the unwanted effects.

An example of the variations of $\dot{h}_p$ with normal acceleration n_z using just the basic signal (uncompensated) is shown in figure 3(a). The improvement in the $\dot{h}_p$ signal with the compensation can be seen by comparing the results in figure 3(b) with those in figure 3(a). The compensation signal also has the unwanted effect of removing from the flight-path accelerometer signal the induced drag which is incurred in a turn. Consequently, the $\dot{h}_p$ signal of figure 3(b) gave the erroneous indication that sufficient thrust was available $\left(\dot{h}_p \approx 0\right)$ during the accelerated condition in turning flight, whereas speed was lost in the turn. To restore the incremental acceleration resulting from turning flight, it is necessary to add a modifying term. Equation (A17), is an expression which relates induced drag to assumed bank angle and is $-2C_{D_{C_L^2}} C_L\left(\frac{1}{\cos \phi} - 1\right)$. Combining the two modifying signals results in one expression $2C_{D_{C_L^2}} C_L\left(n_z - \frac{1}{\cos \phi}\right)$ which was used to compensate the flight-path acceleration signal. The improvement in the pilot's capability of making a level-flight constant-speed turn with the $\dot{h}_p$ indicator driven by the modified compensated signal instead of the compensated signal can be seen by comparing the results in figure 3(c) with the results in figure 3(b).

The modified compensated signal from the flight-path-oriented accelerometer was used to drive each of the three types of displays investigated. The modified compensated signals were expressed as follows:

$$\dot{V} = g\left[\frac{a_{fp}}{g} + 2C_{D_{C_L^2}} C_L\left(n_z - \frac{1}{\cos \phi}\right) - \gamma\right] \tag{1}$$

$$\gamma_p = \frac{a_{fp}}{g} + 2C_{D_{C_L^2}} C_L\left(n_z - \frac{1}{\cos \phi}\right) \tag{2}$$

$$\dot{h}_p = V\left[\frac{a_{fp}}{g} + 2C_{D_{C_L^2}} C_L\left(n_z - \frac{1}{\cos \phi}\right)\right] \tag{3}$$

for the present investigation

$$2C_{D_{C_L^2}} C_L \approx 0.075$$

Expressed in the units in which the signals were displayed, the equations become:

$$\dot{V} \text{ (in knots/min)} = 1143\left[\frac{a_{fp}}{g} + 0.075\left(n_z - \frac{1}{\cos \phi}\right) - \gamma\right] \tag{4}$$

$$\gamma_p \text{ (in deg)} = 57.3\left[\frac{a_{fp}}{g} + 0.075\left(n_z - \frac{1}{\cos \phi}\right)\right] \tag{5}$$

$$\dot{h}_p \text{ (in ft/min)} = 60\, V\left[\frac{a_{fp}}{g} + 0.075\left(n_z - \frac{1}{\cos\phi}\right)\right] \tag{6}$$

These three equations provide signals to the displays for constant true airspeed flight. For constant indicated airspeed flight, the equations are modified by a factor $\frac{1}{K + 1}$ which is a function of Mach number. The derivation of this factor is given in appendix B. For constant indicated airspeed flight, the equations become, expressed in the units in which the signals were displayed,

$$\dot{V}_i \text{ (in knots/min)} = 1143\left[\left(\frac{1}{K + 1}\right)\frac{a_{fp}}{g} + 0.075\left(n_z - \frac{1}{\cos\phi}\right) - \gamma\right] \tag{7}$$

$$\gamma_p \text{ (in deg)} = 57.3\left[\left(\frac{1}{K + 1}\right)\frac{a_{fp}}{g} + 0.075\left(n_z - \frac{1}{\cos\phi}\right)\right] \tag{8}$$

$$\dot{h}_p \text{ (in ft/min)} = 60V\left[\left(\frac{1}{K + 1}\right)\frac{a_{fp}}{g} + 0.075\left(n_z - \frac{1}{\cos\phi}\right)\right] \tag{9}$$

Test Program

Procedure.- The test program consisted of simulator tests starting at prescribed initial flight conditions. The initial flight conditions were an approach at 2000-ft (0.61 km) altitude and 195 knots, a subsonic level-flight condition at altitudes from 10 000 to 20 000 ft (3.05 to 6.10 km) and Mach number 0.6, and a supersonic level-flight condition at altitudes of 50 000 to 60 000 ft (15.22 to 18.28 km) and Mach number 2.0. The test at the approach condition consisted of a 15° heading change to intercept and acquire the ILS (Instrument Landing System) localizer and descent along a 3° glide path to 100-ft (30.5 m) altitude. The subsonic and supersonic flight condition tests consisted of initial level flight followed by climbing and descending turns followed by leveling at a preselected altitude. Speed was to be held constant throughout the test. For each test condition, the pilot used a thrust-management instrument and then repeated the tests without the use of a thrust-management instrument. All three thrust-management instruments were tested at the three initial flight conditions.

Continuous records of altitude, Mach number, indicated airspeed, rate of climb, flight-path angle, flight-path acceleration, normal acceleration, bank angle, rate of change of speed, potential flight-path angle, potential rate of climb, throttle positions, and elevator positions were made. Pilot comments were obtained by use of a written questionnaire.

Pilots.- Piloting personnel used in this investigation consisted of three NASA test pilots, two airline captains, and an aeronautical engineer with piloting experience in light planes and in simulators. Most of the simulation runs from which data were used were made by the aeronautical engineer and an NASA test pilot. Comments were given by all participating pilots.

RESULTS AND DISCUSSION

Sample time histories of airplane performance parameters and throttle position during various maneuvers using each of the three thrust-management displays are given in figures 4 to 12. Comparative results are given for the same maneuver performed without the thrust-management display in each instance. Results are given for climbing and descending turns at subsonic and supersonic speeds, ILS intercept and acquisition, and level flight in an oval flight pattern during which airplane configuration (drag) changes were made.

Answers to questions on a questionnaire were provided by the pilots as part of the investigation of the thrust-management instruments. Four of these questions together with pilot answers are presented in appendix C. A discussion of these answers is presented in the text.

Flight-Path Control

As an indication of flight-path control performance, the deviations in vertical velocity and flight-path angle from the intended value during the test maneuvers were examined. Comparison of the deviations for the same maneuver were made for tests with each of the thrust-management displays and for tests without the display. The result of this comparison indicated that there was no consistent overall difference in task performance as can be seen in the sample results given in figures 4 to 12. This result, however, may have been influenced by the longitudinal response characteristics of the simulated airplane. In the opinion of the pilots, the airplane was slow to respond longitudinally. Consequently, the pilot overcontrolled at times in trying to catch up. This overcontrolling tended to mask out any effects of the individual thrust-management instruments. Some examples of overcontrolling can be seen for each of the thrust-management instruments in figures 4, 6, 7, 10, and 11. The overcontrolling is evident more in the $\dot{V}$ thrust-management presentations (figs. 10 and 11) than in either of the $\dot{h}_p$ or γ_p thrust-management presentations (figs. 4, 6, and 7). This overcontrolling is due to instrument sensitivity and the effect of changing flight-path angle γ which enters directly into the computation of $\dot{V}$. (See eq. (A8).)

In contrast to the $\dot{V}$ instrument, the indices of the $\dot{h}_p$ and γ_p instruments were fairly steady as shown by the results in figures 5, 7, 8, 9, and 12 and showed a small oscillation in figures 4 and 6. The oscillations in figure 4 were generally not greater than ±200 ft/min (61 m/min). This movement did not bother the pilot and indicated that the compensation for normal acceleration was fairly satisfactory, airplane normal accelerations being on the order of ±0.15g. In figure 12(a), the large excursions of $\dot{h}_p$ which occur at approximately 0.7, 2.8, 3.8, 4.6, and 5.7 min are a result of configuration changes and ensuing thrust changes by the pilot. In between the major configuration changes, the $\dot{h}_p$ trace is generally quite smooth.

Speed Control

In general, indicated airspeed was held to about the same degree of tolerance in the tests with and without any of the three thrust-management displays. As can be seen in figures 4 to 9, for the constant indicated airspeed maneuvers, airspeed deviations were generally less than 10 knots from the initial value. For the constant Mach number maneuvers shown in figures 10 and 11, maximum Mach number deviations were generally less than 0.02. An analysis for 78 constant indicated airspeed (IAS) maneuvers showed that the average mean deviations of the indicated airspeed from the initial value was 4.3 knots for the tests with the γ_p and $\dot{h}_p$ displays, 3.6 knots for the tests with the $\dot{V}$ display, and 4.8 knots for the tests without a thrust-management display. This analysis indicates that the pilot did a slightly better job in holding airspeed with the $\dot{V}$ thrust-management display than with either the γ_p or $\dot{h}_p$ thrust-management displays or without any thrust-management display. This result is qualified, however, in the section entitled "Throttle Activity."

The results of figures 4 to 11 also show large variations in required throttle changes which were used in setting up the various constant indicated airspeed or constant Mach number ascents or descents. For example, a throttle change of approximately 50 percent was required for the constant IAS descent of figure 9, whereas a throttle change of only 5 percent was needed for the constant Mach number descent of figure 11. Despite the large variation in thrust trim required, the thrust-management display constantly provided direct readings to the pilot of the thrust trim status of the airplane thus tending to make the pilot's task easier.

Throttle Activity

Throttle activity was analyzed as an indication of the piloting task in managing thrust. The analysis is presented in figure 13 in the form of histograms of the number of throttle motions per minute of test time for 78 tests. The throttle motion count for each test does not include that portion of the test where the pilot was entering into or exiting from a climb or descent task. The throttle motion count was begun immediately following a flight-path change and ended with the initiation of pitching velocity to exit from the maneuver. The figure includes tests of ILS, subsonic, and supersonic flight conditions as shown in figures 4 to 11. The figure is divided into three groups of tests: (1) tests with the γ_p or $\dot{h}_p$ thrust-management display, (2) tests without a thrust-management display, and (3) tests with the $\dot{V}$ thrust-management display. The data for the γ_p and $\dot{h}_p$ thrust-management instruments were combined because of the similarity of the instruments.

The histograms (fig. 13) show that the maximum number of throttle motions per minute of test time is approximately the same with the γ_p or $\dot{h}_p$ thrust-management instruments as without the use of a thrust-management instrument. However, the average number of throttle motions per minute of test time with the γ_p or $\dot{h}_p$ thrust-management instruments is less than one-half the average number of throttle motions without a thrust-management instrument. With the $\dot{V}$ thrust-management instrument, both the maximum and average number of throttle motions per minute is larger than with either of the other two groups of tests. This is possibly due to a combination of factors such as nonoptimum instrument sensitivity and the tendency of the pilots to overcontrol the airplane – both these factors adversely affecting a single movement display more than a two-movement display. (See ref. 4.) In this program, there was not a sufficient number of tests of configuration A, B, or C to separate any effects of display sensitivity.

The usefulness of the $\dot{h}_p$ thrust-management instrument in reducing unnecessary throttle motion is especially evident in the results shown in figure 12. An oval flight pattern was flown which consisted of 1-min legs followed by 180° turns. At 1-min intervals, the copilot initiated configuration drag changes such as flap and gear changes. The times at which these configuration changes occurred are shown in the figure. With the use of the $\dot{h}_p$ thrust-management instrument, major throttle changes occurred approximately at the time of major drag changes with very little throttle motion in between drag changes. Without the use of a thrust-management instrument, the throttle was being continuously changed as the pilot hunted for trimmed thrust.

Pilot Comments

Improvement in performance of tasks.- The general opinion among the pilots was that each of the $\dot{h}_p$, γ_p, or $\dot{V}$ thrust-management instruments provided an improvement in control of speed, altitude, and flight path. (See appendix C for detailed comments.) This improvement was brought about by providing a quick method of accurately setting thrust for climb, descent, or level flight; thus this portion of the pilot's task was reduced and more time was left for the other flight-control tasks.

Further, the thrust-management instruments provided a means of speed control through the operating range of an airplane as well as maximum climb or descent attitude for a particular thrust setting and at constant speed. The thrust-management instruments also provided a fairly easy and accurate way of controlling thrust in the transition from one flight condition to another. There was some question as to whether the γ_p and $\dot{h}_p$ instruments were of value for the landing task using the ILS. An NASA test pilot specified that the $\dot{h}_p$ or γ_p instruments were desirable in setting up the initial ILS conditions; but while using ILS guidance, the $\dot{V}$ thrust-management quantity displayed on the slow-fast meter was preferred. The $\dot{V}$ thrust-management quantity was indicated to provide the anticipation and magnitude of thrust control which was needed on the ILS.

Level of pilot workload.- The general piloting opinion was that there was a decrease in mental workload with the use of any of the thrust-management instruments. The information provided by the thrust-management instrument also reduced the time spent in throttle manipulation while giving the pilot continuous information on his thrust status. It was generally recognized that there was some increase in the pilot's scan pattern workload.

There were several adverse comments on the location of the thrust-management instrument. (See fig. 1.) The thrust-management instrument was located in an area selected for a rate-of-climb meter since two of its displays have to do with the climbing or descending status of the airplane. Therefore, the location was believed to be appropriate for investigation of either the $\dot{h}_p$ or γ_p thrust-management instruments. Pilot criticism of investigation of the $\dot{V}$ thrust-management display in the location shown in figure 1 is probably justifiable; a better location for this display would be close to the airspeed meter or on the slow-fast meter of the flight attitude indicator.

Several pilots felt that the addition of the thrust-management instrument did not eliminate any of the other instruments but did decrease the time needed to be spent scanning the other instruments. These pilots stated that in further development of the thrust-management instruments, testing under actual flight conditions was needed.

Information presentation.- In the preliminary evaluation of the display, the general opinion was that motions on the index in response to fore and aft stick motion were distracting. These motions which were caused by induced drag changes were almost entirely removed by compensating for the induced drag as explained in the section "Thrust-management display signals;" this was a vast improvement for the pilot. There were unnecessary motions on the pointer at times due to overcontrol. These motions were referred to as "chasing the bug" and required some adjustment by the pilot either to ignore the motions or to eliminate them by not overcontrolling. There was no criticism of any of the thrust-management instruments appearing to give false information.

The design of the $\dot{h}_p$ and γ_p thrust-management meters was criticized. The pointer and index when close together tended to obscure the numerals. For small deflections where the scale was expanded to include smaller marked increments, the partial obscuring of the numerals made reading of the instrument especially difficult. This difficulty was of more concern with the γ_p instrument than with the $\dot{h}_p$ instrument because of the small flight-path angles generally incurred at supersonic speeds.

Pilot comments of the thrust-management displays were strongly influenced by the display sensitivity. At subsonic speeds, both the $\dot{h}_p$ and γ_p instruments were rated as having generally satisfactory sensitivitv. The 3000-ft/min (914 m/min) rate of climb of figure 4 corresponded to 61° meter movement and the 3° flight-path angle (2000-ft/min (609 m/min) rate of climb) of figure 8 corresponded to a 35° pointer deflection, thus showing that both instruments had about the same sensitivity subsonically (approximately 55 ft/min (16.7 m/min) per degree). For tests in which there was a lot of overcontrol activity, there were comments of the $\dot{h}_p$ and γ_p instruments being slightly oversensitive. At supersonic speeds, the sensitivity of the $\dot{h}_p$ instrument was satisfactory, whereas the sensitivity of the γ_p instrument was low. The reason for the apparent decrease in sensitivity of the γ_p instrument is that as true speed increases, the climb or descent angle decreases in order to hold constant a rate of climb or descent.

The $\dot{V}$ thrust-management display, configuration A (table III), was rated as quite sensitive on the ILS and at the subsonic test condition and satisfactory at the supersonic test condition. Configuration B having one-half the sensitivity of configuration A was satisfactory to slightly overly sensitive on the ILS and at the subsonic test condition and slightly insensitive at the supersonic test condition. Configuration C (table III) was displayed on the slow-fast meter of the flight attitude director. The sensitivity of the slow-fast display was slightly less than one-half the sensitivity of the display of configuration B. The reason for the reduced sensitivity was the small range of needle movement (±0.33 in. (±0.84 cm)) on the slow-fast display. Satisfactory ratings of configuration C were obtained on ILS and at subsonic Mach numbers because of the reduced sensitivity and the more favorable display location for the $\dot{V}$ display. There was some criticism that the meter pegged on the ILS test condition, which was undesirable. At supersonic speeds, the $\dot{V}$ thrust-management displayed on the slow-fast meter was criticized as being insensitive.

CONCLUDING REMARKS

Three displays, each of which provided information to be used in thrust management of an airplane, were evaluated. These displays were (1) rate of change of velocity $\dot{V}$, knots/min; (2) potential flight-path angle γ_p, deg; and (3) potential rate of climb $\dot{h}_p$, ft/min. The test apparatus consisted of a fixed-base four-engine jet cockpit and analog computers. Pilots with a broad range of experience simulated flights involving thrust-management changes both with and without the thrust-management displays. Data were obtained as time histories, histograms, and pilot comments.

The results show that, on the average, about one-half the number of throttle motions per minute of test occurred for tests with the γ_p or $\dot{h}_p$ thrust-management display as compared with tests without a thrust-management display. Also, on the average a slightly higher number of throttle motions per minute of test occurred for tests with the $\dot{V}$ thrust-management display when compared with tests without a thrust-management display. The average mean deviations of the indicated airspeed from the initial value for tests with the $\dot{V}$ thrust-management display were slightly less than the average mean deviations for tests with the $\dot{h}_p$ or γ_p thrust-management display or without any thrust-management display. The pilots commented that the thrust-management displays provided a fairly fast and accurate method of thrust management and that the scan pattern workload was increased but the mental workload was decreased with the use of the thrust-management displays.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., August 3, 1970.

APPENDIX A

DEVELOPMENT OF MATHEMATICAL RELATIONS

The mathematical expression for the relationship between the forces and the acceleration along the flight path for a climbing or descending aircraft may be written as

$$T \cos \alpha - D - W \sin \gamma = \frac{W}{g} \dot{V} \tag{A1}$$

For the same conditions, the acceleration measured by an accelerometer alined with the flight path is

$$a_{fp} = \dot{V} + g \sin \gamma \tag{A2}$$

or in g units,

$$\frac{a_{fp}}{g} = \dot{V} \frac{1}{g} + \sin \gamma \tag{A3}$$

From equations (A1) and (A3), the following equation may be written:

$$\frac{T \cos \alpha - D}{W} = \frac{a_{fp}}{g} = \dot{V} \frac{1}{g} + \sin \gamma \tag{A4}$$

For small angles, equation (A4) can be reduced to

$$\frac{T - D}{W} = \frac{a_{fp}}{g} = \dot{V} \frac{1}{g} + \gamma \tag{A5}$$

Since for small angles $\gamma = \frac{\dot{h}}{V}$, equation (A5) may also be written as

$$\frac{T - D}{W} = \frac{a_{fp}}{g} = \dot{V} \frac{1}{g} + \frac{\dot{h}}{V} \tag{A6}$$

Equation (A6) may be rearranged to give

$$\frac{(T - D)V}{W} = \frac{a_{fp}V}{g} = \dot{V} \frac{V}{g} + \dot{h} \tag{A7}$$

From the relationship in equation (A5),

$$\dot{V} = g\left(\frac{a_{fp}}{g} - \gamma\right) \tag{A8}$$

With γ_p substituted for γ and $\dot{V} = 0$,

$$\gamma_p = \frac{a_{fp}}{g} \tag{A9}$$

From equation (A7) with $\dot{h}_p$ used for $\dot{h}$ and $\dot{V} = 0$,

$$\dot{h}_p = \frac{a_{fp}V}{g} \tag{A10}$$

Compensation to the basic flight-path accelerometer signal for induced drag changes resulting from the accelerated flight is determined as follows. First equation (A5) is repeated:

$$\frac{a_{fp}}{g} = \frac{T - D}{W}$$

where

$$D = \left(C_{D,o} + C_{D_{C_L{}^2}} C_L{}^2\right)qS \tag{A11}$$

For 1g flight,

$$C_L = \frac{W}{qS}$$

For accelerated flight, the incremental change in lift coefficient from a 1g-flight value may be expressed as

$$\Delta C_L = \frac{W}{qS}(n_z - 1) \tag{A12}$$

The effect of the change in lift coefficient on drag may be found by differentiating equation (A11) with respect to lift coefficient. Then for an incremental change in lift coefficient ΔC_L the change in drag may be expressed as

$$\Delta D = 2C_L C_{D_{C_L{}^2}} qS \, \Delta C_L \tag{A13}$$

The change in acceleration along the flight path due to the change in drag is obtained from equation (A5) as

$$\frac{\Delta a_{fp}}{g} = \frac{-\Delta D}{W} \tag{A14}$$

Upon substituting equation (A12) into equation (A13) and equation (A13) into equation (A14), then equation (A14) becomes

$$\frac{\Delta a_{fp}}{g} = -2C_L \, C_{D_{C_L{}^2}} (n_z - 1) \tag{A15}$$

A formula for an additional signal to modify the compensating signal for turning flight is determined as follows. In level (nonturning) flight,

$$L = W$$

In constant altitude turning flight,

$$L = \frac{W}{\cos \phi}$$

Therefore, the change in lift due to change in back angle expressed in coefficient form is

$$\Delta C_L = \frac{\Delta L}{qS} = \frac{W}{qS}\left(\frac{1}{\cos \phi} - 1\right) \tag{A16}$$

If equation (A16) is substituted into equation (A13) and equation (A13) into equation (A14), then the change in acceleration along with flight path due to the change in normal acceleration caused by turning flight is

$$\frac{\Delta a_{fp}}{g} = -2C_L \, C_{D_{C_L{}^2}} \left(\frac{1}{\cos \phi} - 1\right) \tag{A17}$$

APPENDIX B

DEVELOPMENT OF INDICATED-AIRSPEED ADAPTATION

Equations which give impact pressures for subsonic flow and supersonic flow are as follows:

$$q_c = p\left(1 + 0.2\,\frac{V^2}{kRT}\right)^{\frac{k}{k-1}} - p \tag{B1}$$

$$q_c = \frac{k+1}{2}\,pM^2\left[\frac{(k+1)^2M^2}{4kM^2 - 2(k-1)}\right]^{\frac{1}{k-1}} - p \tag{B2}$$

Equations (B1) and (B2) are differentiated with respect to time keeping q_c constant to obtain the rate of change of speed in a climb which is necessary to hold impact pressure constant.

Differentiating equation (B1) and using the relations $a^2 = kRT$, $dp = -\rho g\,dh$, $p = \rho RT$, and $\frac{dh}{dt} = V\gamma$ result in the following equation:

$$\left\{\left[\frac{\left(1 + 0.2M^2\right)^{\frac{k}{k-1}} - 1}{\left(1 + 0.2M^2\right)^{\frac{1}{k-1}}}\right] + 0.7\,\frac{RM^2}{g}\,\frac{dT}{dh}\right\}\gamma = \frac{1}{g}\,\dot{V} \tag{B3}$$

or

$$K_1\gamma = \frac{1}{g}\,\dot{V} \tag{B4}$$

where, for a standard atmosphere, K_1 (used to represent term in braces in eq. (B3)) is a function of M and $\frac{dT}{dh}$.

A differentiation of equation (B2) with respect to time and using the relations $a^2 = kRT$, $dp = -\rho g\,dh$, $p = \rho RT$, and $\frac{dh}{dt} = V\gamma$ result in the following equation:

$$\left\{\frac{\frac{1}{2}\left[1.2M^2\left(\frac{5.76M^2}{4kM^2 - 0.8}\right)^{2.5} - 1\right]}{\frac{1.2}{k}\left(\frac{5.76M^2}{4kM^2 - 0.8}\right)^{2.5} + 3M^2\left(\frac{5.76M^2}{4kM^2 - 0.8}\right)^{1.5}\left[\frac{5.76}{k(4kM^2 - 0.8)} - \frac{23.05M^2}{(4kM^2 - 0.8)^2}\right]} + 0.7\frac{RM^2\frac{dT}{dh}}{g}\right\}\gamma = \frac{1}{g}\dot{V} \tag{B5}$$

or

$$K_2\gamma = \frac{1}{g}\dot{V} \tag{B6}$$

where for a standard atmosphere K_2 (used to represent term in braces in eq. (B5)) is a function of M and $\frac{dT}{dh}$.

Substitute equations (B4) or (B6) for $\frac{1}{g}\dot{V}$ into equation (A5) and replace K_1 or K_2 with K and γ with γ_p to obtain the following relation:

$$\gamma_p = \left(\frac{1}{K + 1}\right)\frac{a_{fp}}{g} \tag{B7}$$

where γ_p is the flight-path angle which would allow a holding of constant indicated airspeed. The term $\frac{1}{K + 1}$ is evaluated for standard atmospheric conditons and is presented in figure 14.

Likewise,

$$\dot{h}_p = \left(\frac{1}{K + 1}\right)V\frac{a_{fp}}{g} \tag{B8}$$

and

$$\dot{V} = \left(\frac{1}{K + 1}\right)\frac{a_{fp}}{g} - \gamma \tag{B9}$$

APPENDIX C

SUMMARY OF QUESTIONS AND ANSWERS FROM THE PILOT EVALUATION SHEETS

Question: Did use of the test instrument improve speed control, attitude control, or flight-path control?

Answers:

Pilot A – $\dot{V}$ instrument improves speed control by providing lead information.

γ_p improved all three – provides the lead information necessary to make smooth climb and level-off entries and trim power for desired Mach.

Pilot B – Yes. The instrument (γ_p) permitted holding accurate flight-path angle, which in turn allowed a fairly smooth and nearly constant rate of climb and pitch attitude.

In climbs – yes – set rate of climb to match thrust rate of climb $(\dot{h}_p)$ and IAS held constant. In level flight – (a) as good but no better than altimeter for altitude control; (b) permitted thrust trim for speed control after acceleration or deceleration.

Pilot C – $\dot{V}$ improved speed control on ILS glide path providing anticipation and magnitude.

γ_p improved all three except in the ILS. γ_p is useful primarily for establishing glide path with correct thrust. Reference <u>only</u> thereafter.

$\dot{h}_p$ improved all three, except strong tendency to oscillate about the "bug." Shows promise.

Pilot D – Yes, for initial thrust settings on ILS (γ_p). The airplane response is so sluggish (aft c.g. location) that continued overshooting of pitch attitude occurs after transitioning from one flight path to another.

Pilot E – Yes. They $(\dot{V}, \gamma_p, \dot{h}_p)$ enable more prompt and accurate thrust settings for any selected airspeed. The instrument $(\dot{h}_p)$ provided accurate indication for the thrust necessary to make good a desired rate of climb, thus making possible direct entry to any particular climb or descent attitude while maintaining a specific speed.

Pilot F – Yes. These instruments $(\dot{V}, \gamma_p, \dot{h}_p)$ give accurate readout of thrust trim versus airspeed. Allow most accurate thrust management.

Question: Did use of the test instrument result in an increase or decrease in pilot workload?

Answers:

Pilot A – Impressive reduction in mental workload involved in holding airspeed and Mach in the level off from climb and at the end of acceleration ($\dot{V}$ instrument).

Decreased workload (γ_p) – one or two power adjustments for trimmed Mach. Reduced the tendency to overcontrol pitch attitude.

Pilot B – Decrease in workload. Without the instrument (γ_p) the thrust setting for holding altitude and speed is not known and the pilot must try to find it by trial and error, which requires several adjustments of the throttles before finally locating trim thrust.

Definite decrease in pilot workload in climbs in holding constant IAS with $\dot{h}_p$ instrument when compared with task without instrument. In level flight – a somewhat decrease in workload in thrust trimming.

Decrease in workload for same task without $(\dot{V})$ instrument use.

Pilot C – $\dot{V}$ allowed more attention to be paid to ILS tracking.

Decrease. γ_p instrument is a very useful aid.

"Chasing the bug" took too much time $(\dot{h}_p)$. Does not eliminate other instruments but does decrease use of the other instruments. Has considerable promise of reducing workload and increasing precision.

Pilot D – Some additional instrument scanning was necessary but overall workload was definitely decreased.

Pilot E – Increase. The instrument $(\dot{V})$ was apart from the primary reference flight instruments. Therefore, the scan pattern was increased to an unnecessary degree incorporating the data. The information should be presented by the flight director in a separate selected mode to the extent possible. What cannot be included should be presented in a closely associated position, that is, slow/fast display on IAS.

Pilot F – Increase, because of additional instrument $(\dot{V})$ and particularly its location.

Question: Was the instrument ever distracting or did it appear to give false information?

Answers:

Pilot A – Do not like short-period acceleration effect on $\dot{V}$ pointer – pilot learning required.

No (referring to γ_p thrust trim instrument).

Pilot B – Fore and aft motions of the stick cause movement of the γ_p pointer and these were distracting at first until familiarization with the instrument – then these motions were ignored and the instrument was used for trim adjustment only when the stick was not being moved.

Yes. The $\dot{h}_p$ pointer moved substantially with push and pull of the longitudinal control. Thrust trim could not be set accurately unless the longitudinal control was stationary.

At low speed and altitude for ILS, the sensitivity of the $\dot{V}$ caused pointer to vary ±3 knots/min for pitch adjustments on ILS glide slope – this is distracting.

Pilot C – (configuration A, table III) Too sensitive – against stops much of the time and difficult to adjust at zero.

γ_p, tendency to "chase the bug" at first. Does not keep you on ILS path although useful in establishing path at outset.

$(\dot{h}_p)$ Large overshoots of climb pointer and slow airplane response to control are distracting. I did have to stop and "think out" the instrument several times.

Pilot D – No. I got confused at times probably due to lack of familiarity when making simultaneous thrust and altitude changes, in that I would momentarily forget which pointer represented excess thrust and which represented flight path.

Pilot E – No, only to the extent of the position $(\dot{V})$.

Pilot F – No, $(\dot{V}, \gamma_p, \dot{h}_p)$ very easy to use and interpret information.

Question: Are there any general comments?

Answers:

Pilot D – The simulated airplane response is sluggish – overshoots pitch attitude.

Pilot C – Airplane sluggish and overshoots. Dynamics of this airplane longitudinally are poor.

Pilot B – Increase in static margin reduces motion of airplane needle because do not overcontrol. Airplane still sluggish though.

REFERENCES

1. Gannett, James R.: New Flight Instrumentation for Future Transport Aircraft. [Preprint] 670327, Soc. Automot. Eng., Apr. 1967.

2. Mahoney, John J.; and Bennett, Donald A.: A Comparative Evaluation of Three Techniques for Measurement of Level Flight Accelerations. AFFTC Tech. Note No. 54-2, U.S. Air Force. (Available from DDC as AD 116 046.)

3. Allen, Willie L.; and Weight, Robert H.: The Use of Flightpath Accelerometers in Performance Flight Testing. Proceedings of the 13th Annual Air Force Science & Engineering Symposium, Vol. II, 1966. (Available from DDC as AD 641 1922.)

4. Briggs, George E.: Pursuit and Compensatory Modes of Information Display: A Review. AMRL-TDR-62-93, U.S. Air Force, Aug. 1962.

TABLE I

SIMULATED AIRCRAFT CHARACTERISTICS

Mach number	Altitude		W/S		c. g. location, percent mean aerodynamic chord	Longitudinal control characteristics (augmented condition), deg/g	Short period			Phugoid	$\left(\frac{T - D}{W}\right)_{max}$	L/D
							Unaugmented		Augmented			
	ft	km	lb/ft^2	N/m^2			P, sec	$t_{1/2}$, sec	$t_{1/2}$, sec	P, sec		
0.3	2 000	0.61	45	2150	63	6	12	1.4	Critically damped	Not available		[1]6.0
.6	10 000	3.05	61	2920	63	3	8.5	1.7	Critically damped	90	[2]0.21	14.8
2.0	55 000	16.8	61	2920	63	8	5.8	3.2	0.5	180	[3]0.08	7.8
.3	2 000	.61	45	2150	60	11	8.9	1.8	.7	Not available		[1]6.0
.6	10 000	3.05	61	2920	60	8	6.3	1.5	Critically damped	90	[2]0.21	14.8
2.0	55 000	16.8	61	2920	60	14	4.2	2.6	.5	180	[3]0.08	7.8

[1]Flaps at landing condition.

[2]Maximum dry thrust.

[3]Maximum afterburning thrust.

TABLE II

PRIMARY FLIGHT INSTRUMENTS SHOWN IN FIGURE 1

Instrument	Movement classification	Smallest increment displayed
Flight director: pitch	Tape	[1] 5°
Flight director: bank	Dial	10°
Horizontal situation heading display	Dial	5°
Airspeed	Dial (drum-pointer)	2 knots
Mach	Dial (counter-pointer)	0.01 M
Rate of climb	Tape	100 ft/min (30.5 m/min) between 0-1500 ft/min (457 m/min) (not shown)
Altimeter	Dial (counter drum pointer)	20 ft (6.1 m)

[1] The expanded pitch scale was not used in these tests.

TABLE III

DESCRIPTION OF THE THRUST-MANAGEMENT INSTRUMENTS

Configuration	Scale	Units	Minimum division	Maximum scale	Indicator	Quantity displayed	Maximum deflection of indicator
A	Nonlinear	knots/min	2.5	±100	Pointer	$\dot{V}$	±163.5 deg
B	Nonlinear	knots/min	5.0	±200	Pointer	$\dot{V}$	±163.5 deg
[1]C	Nonlinear	knots/min	---	±66.6	Pointer	$\dot{V}$	±0.33 in. (±0.84 cm)
D	Linear	deg	.5	±14	Index	γ_p	±163.5 deg
	Linear	deg	.5	±14	Pointer	γ	±163.5 deg
E	Linear	ft/min (m/min)	250 (76)	±8000 (±2440)	Index	$\dot{h}_p$	±163.5 deg
	Linear	ft/min (m/min)	250 (76)	±8000 (±2440)	Pointer	$\dot{h}$	±163.5 deg

[1] Displayed on the slow-fast indicator.

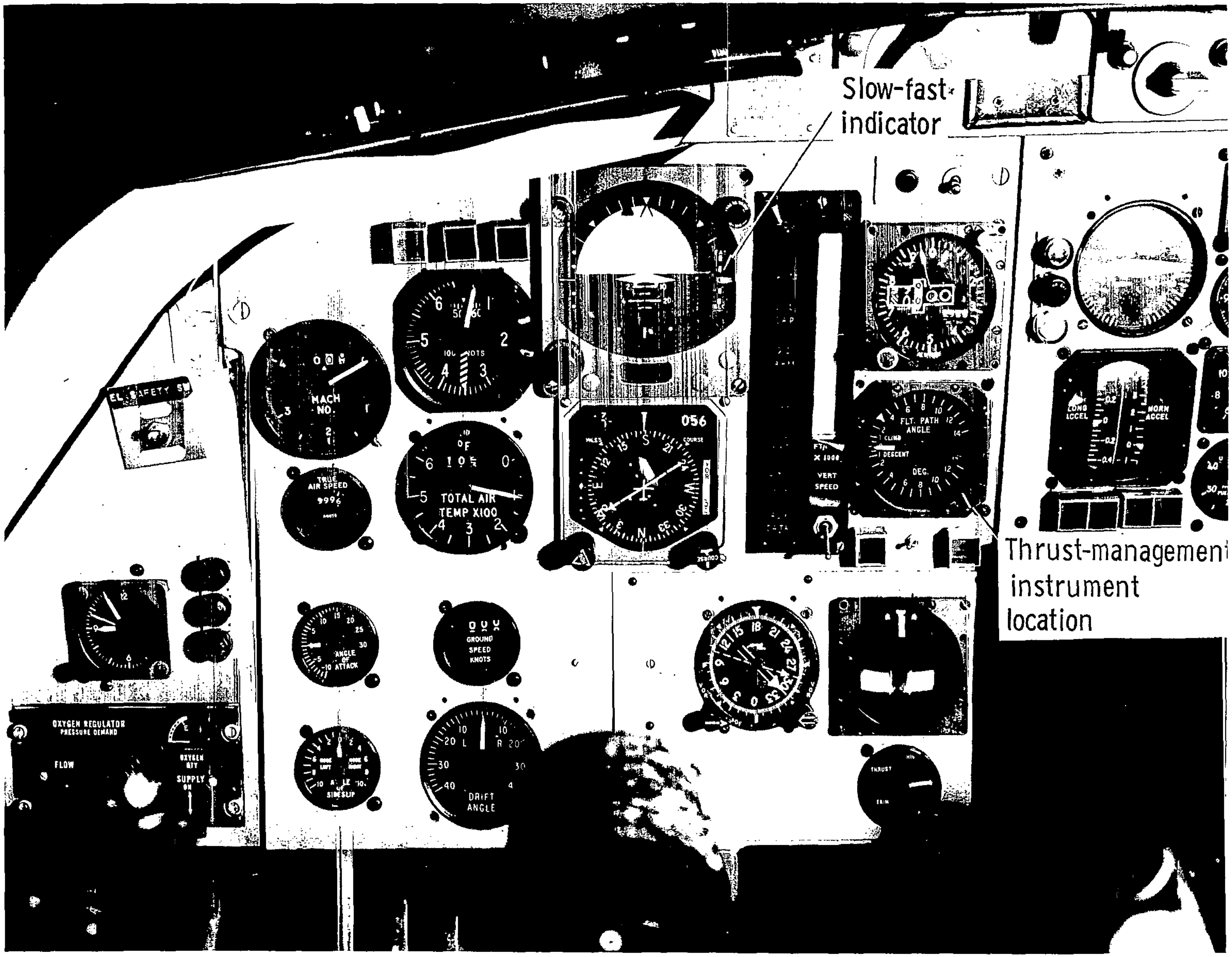

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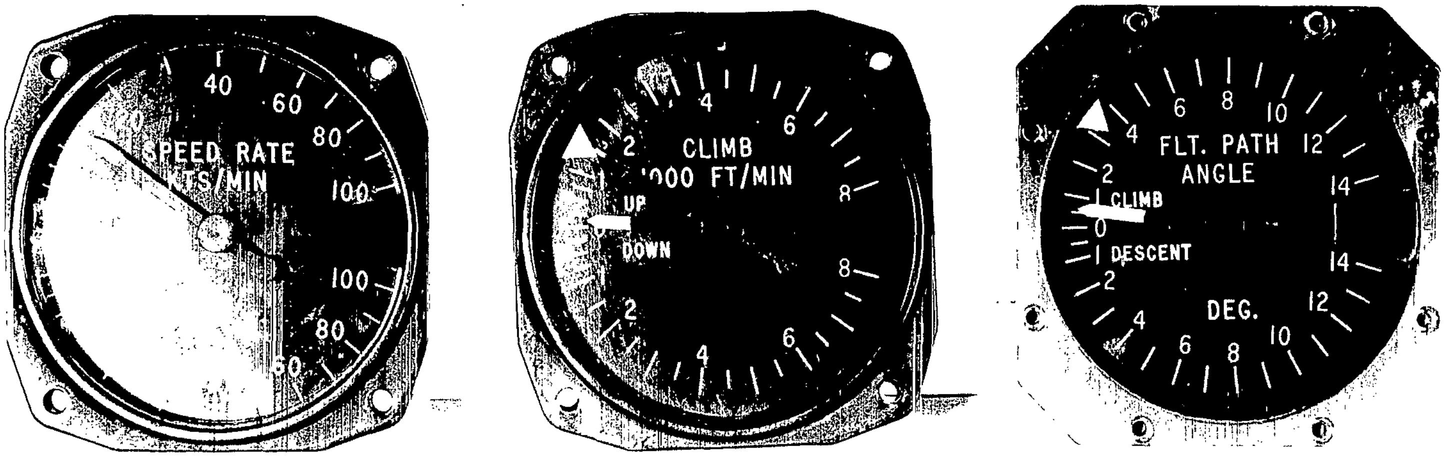
Figure 1.- Pilot's instrument panel used in thrust-management instrument investigation.



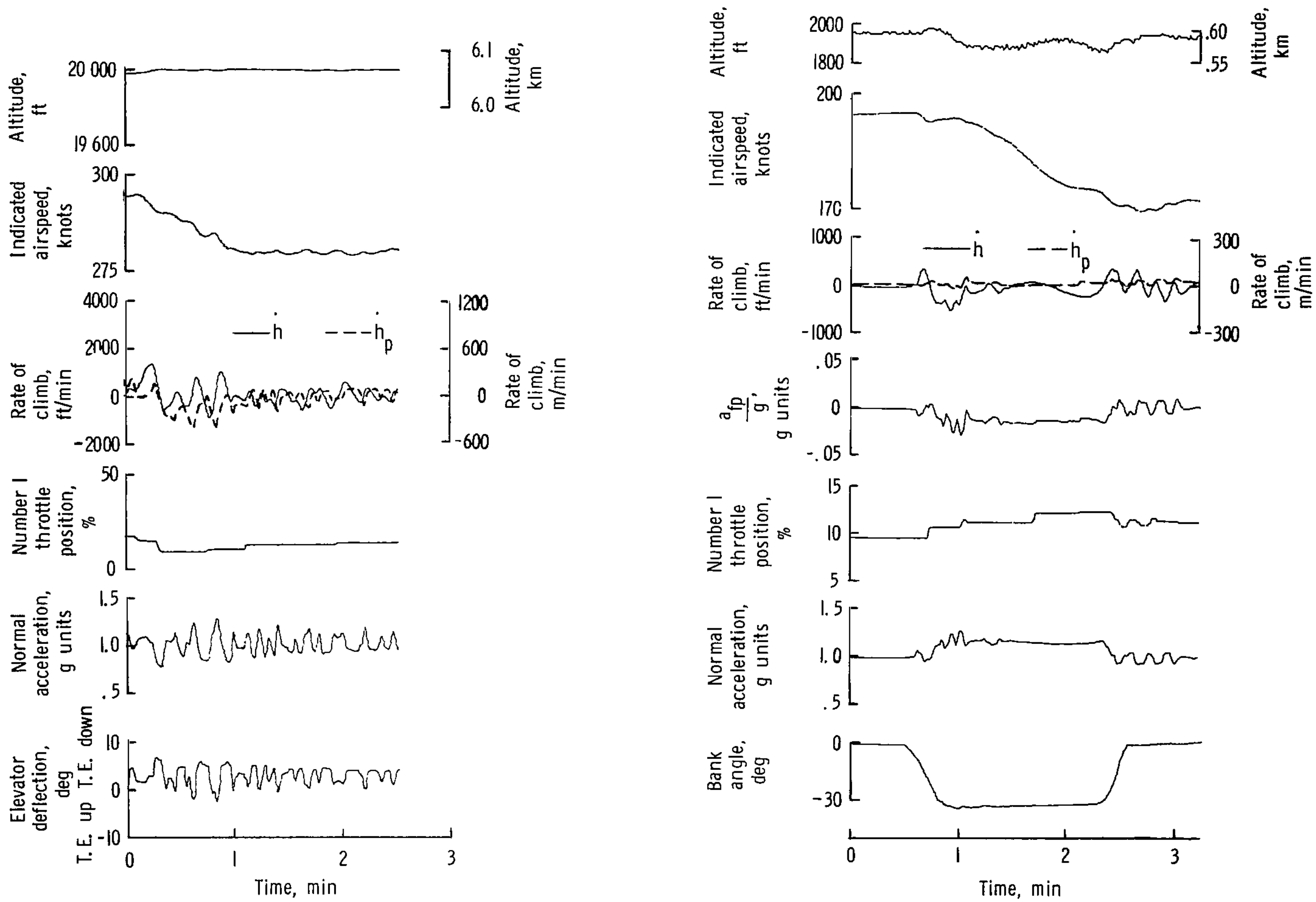
$\dot{V}$
Rate of change
of speed

$\dot{h}_p$
Potential rate
of climb

γ_p
Potential flight-path
angle

L-69-1443.1

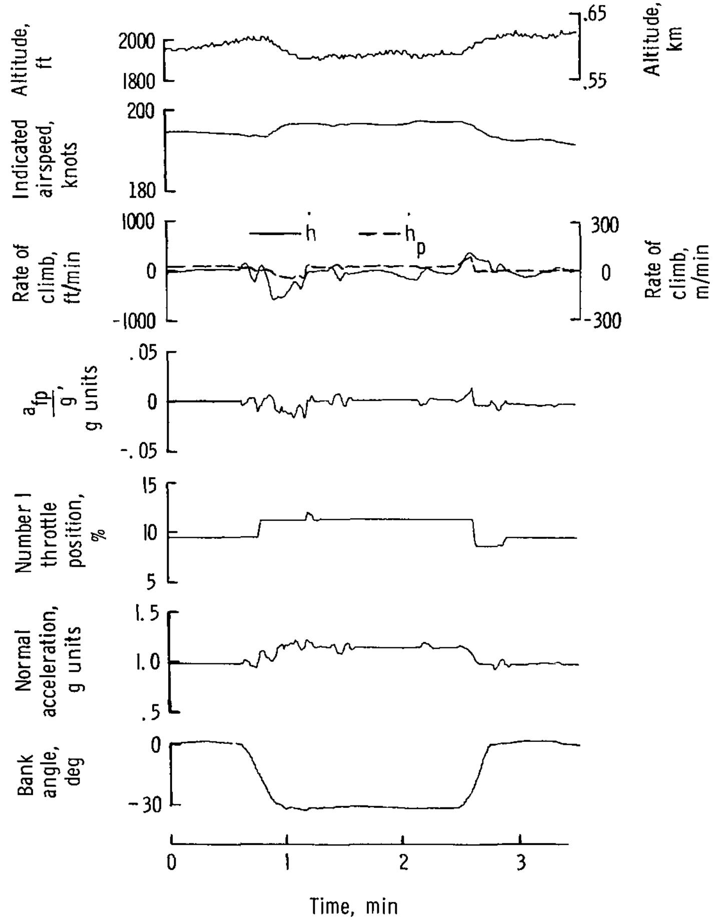
Figure 2.- Three meter displays used in thrust-management investigation.



(a) Level flight; basic $\dot{h}_p$ signal.

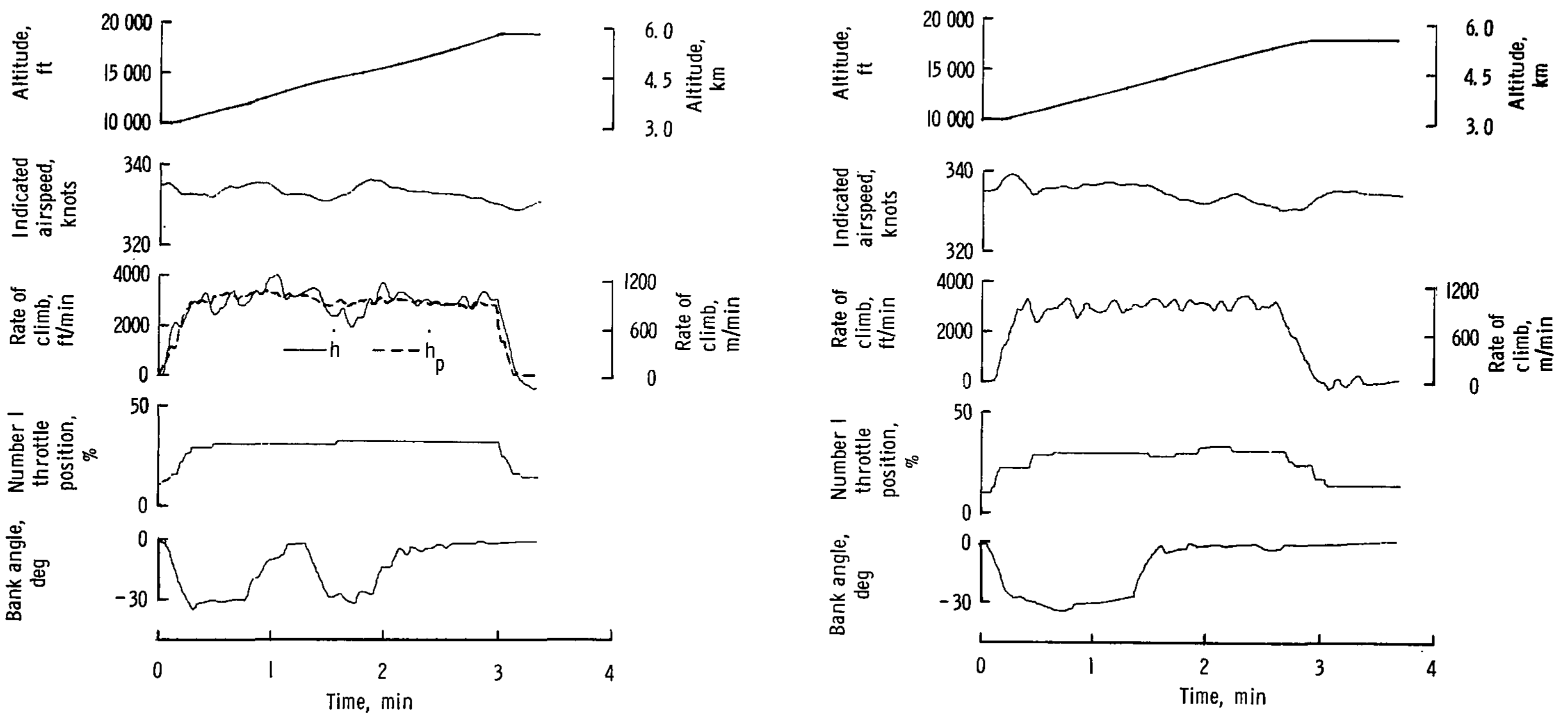
(b) Level-flight turn; $\dot{h}_p$ signal modified to include $0.075(n_z - 1)$ term.

Figure 3.- Time histories of three runs, a level-flight run and two level-flight turns, in which the thrust-management signal $\dot{h}_p$ was used in its various stages of compensation.



(c) Level-flight turn; $\dot{h}_p$ signal modified to include $0.075\left(n_z - \dfrac{1}{\cos\phi}\right)$ term.

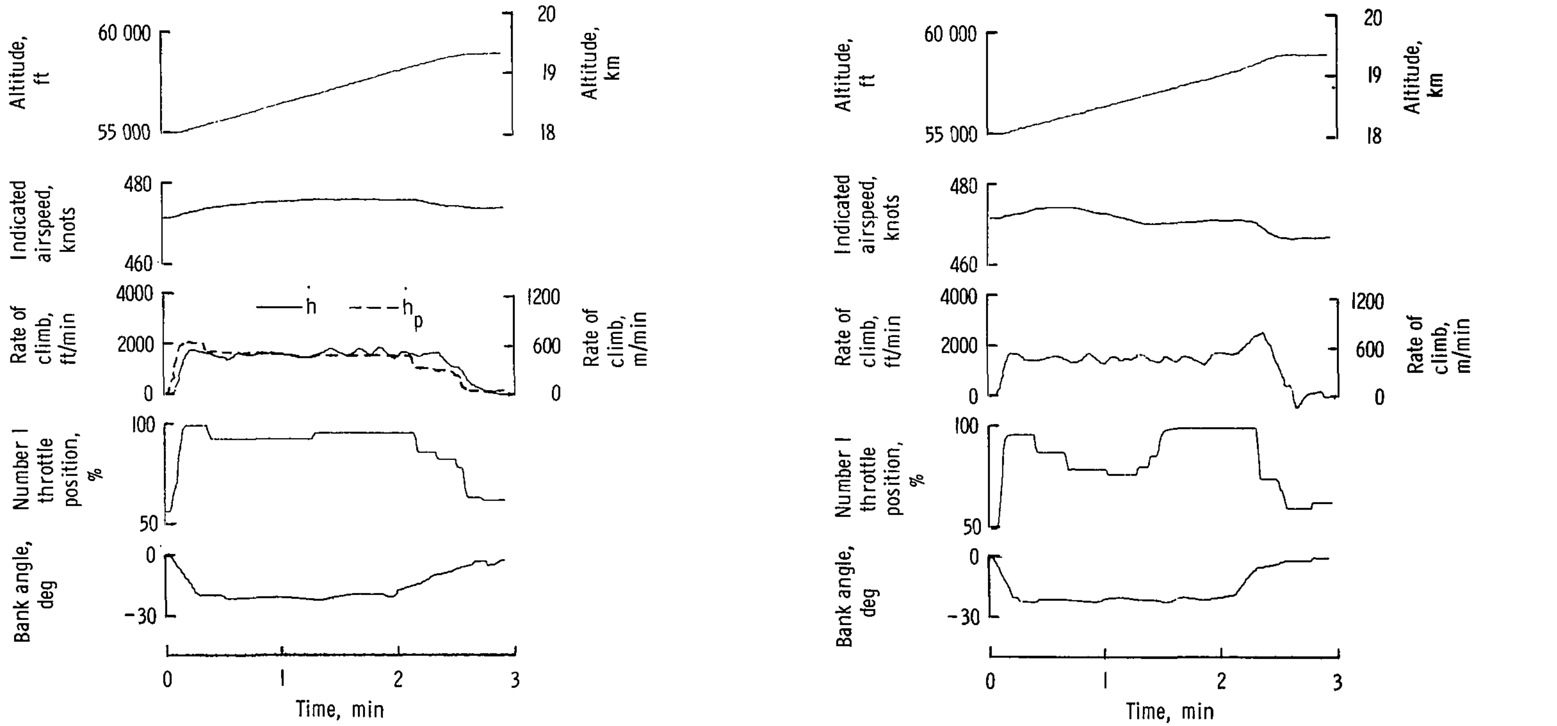
Figure 3.- Concluded.



(a) With $\dot{h}_p$ thrust-management instrument.

(b) Without $\dot{h}_p$ thrust-management instrument.

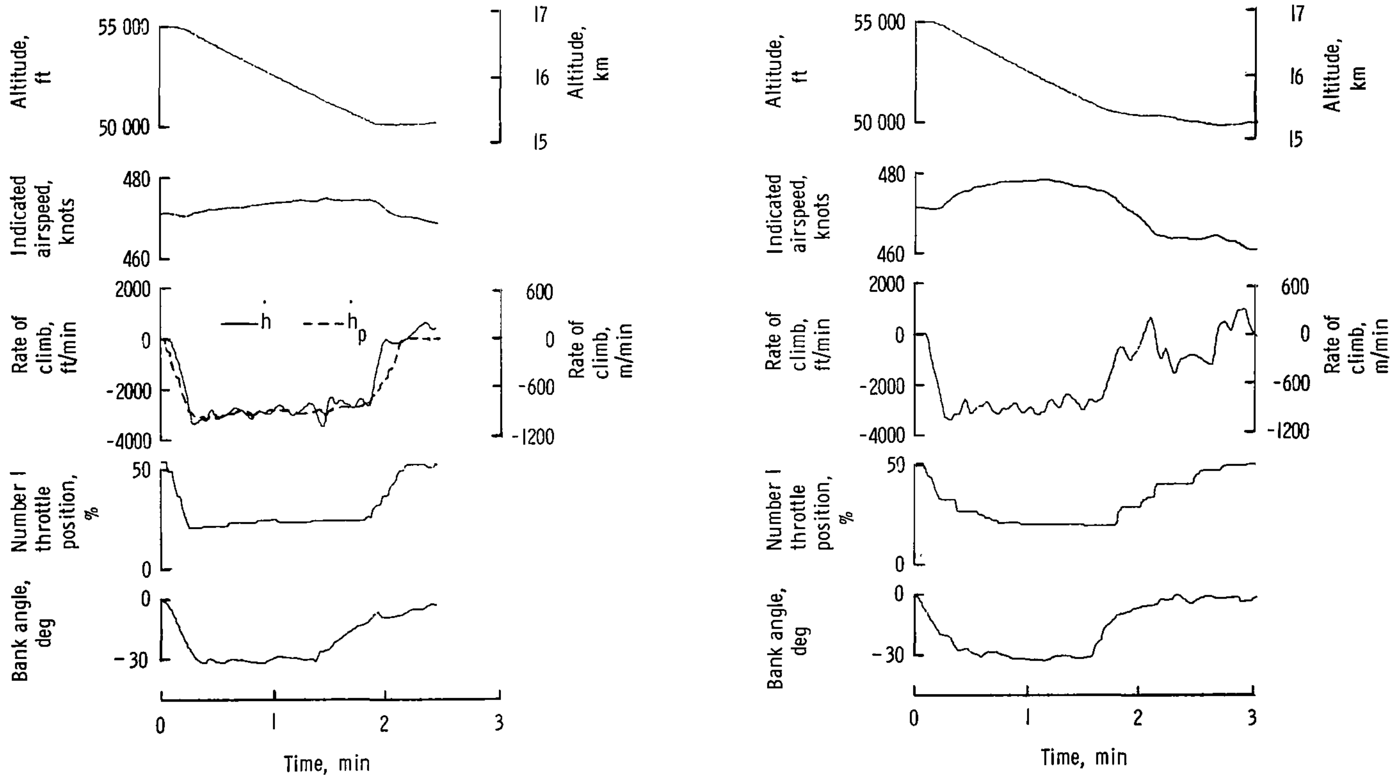
Figure 4.- Time histories of constant indicated airspeed climbing turns at subsonic speeds both with and without $\dot{h}_p$ thrust-management instrument. Forward center-of-gravity location.



(a) With $\dot{h}_p$ thrust-management instrument.

(b) Without $\dot{h}_p$ thrust-management instrument.

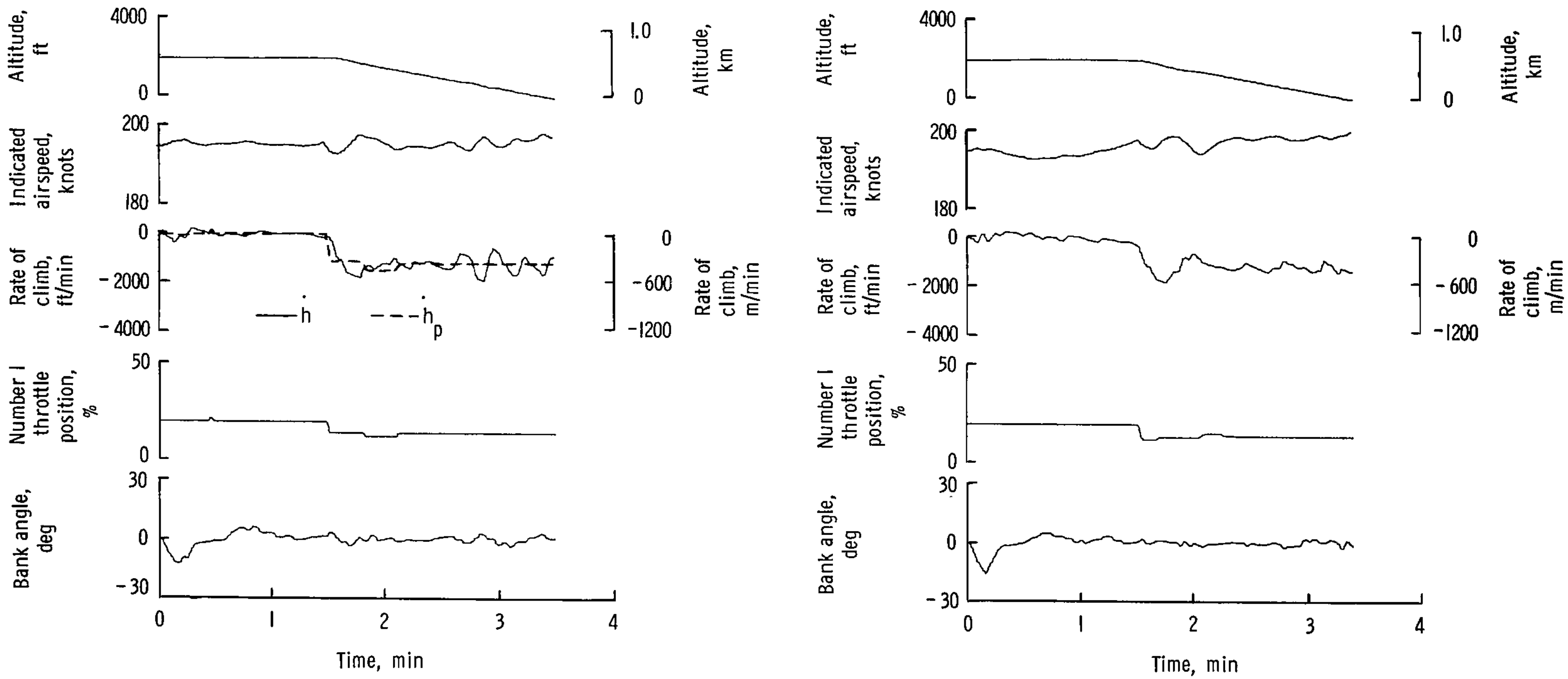
Figure 5.- Time histories of constant indicated airspeed climbing turns at supersonic speeds both with and without $\dot{h}_p$ thrust-management instrument. Forward center-of-gravity location.



(a) With $\dot{h}_p$ thrust-management instrument.

(b) Without $\dot{h}_p$ thrust-management instrument.

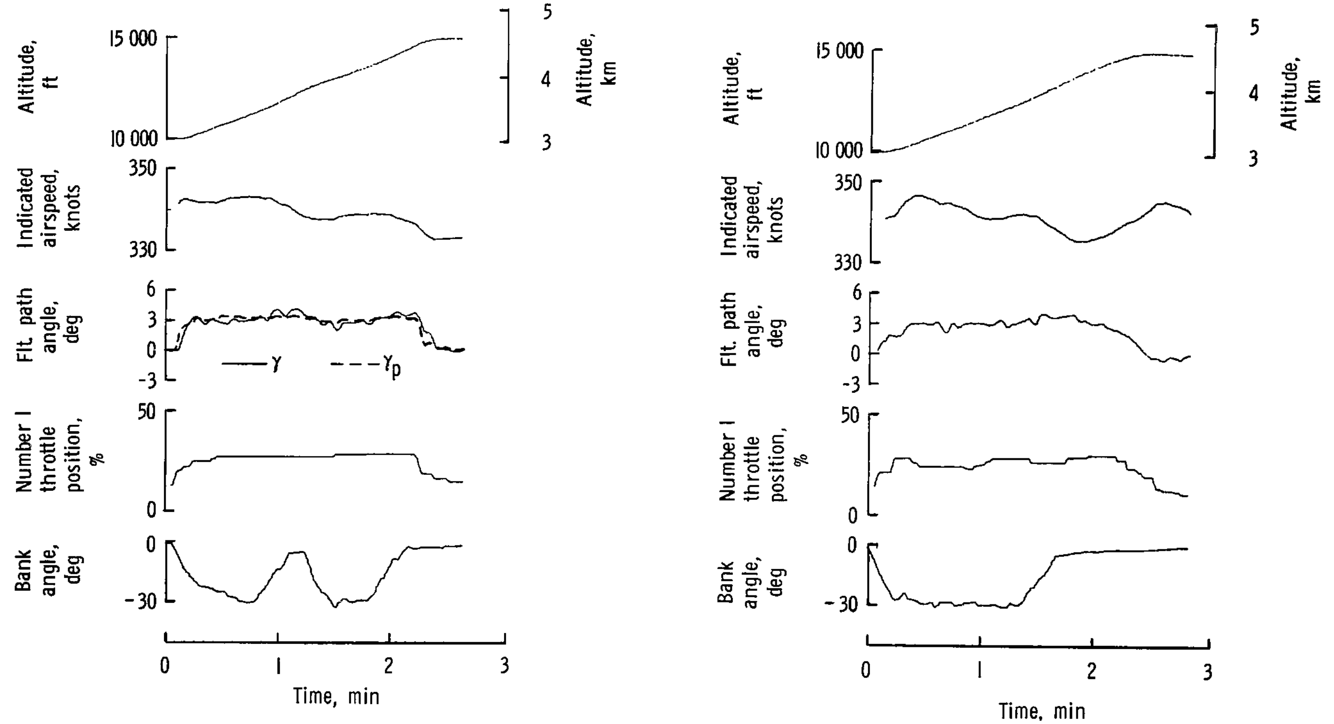
Figure 6.- Time histories of constant indicated airspeed descending turns at supersonic speeds both with and without $\dot{h}_p$ thrust-management instrument. Forward center-of-gravity location.



(a) With $\dot{h}_p$ thrust-management instrument.

(b) Without $\dot{h}_p$ thrust-management instrument.

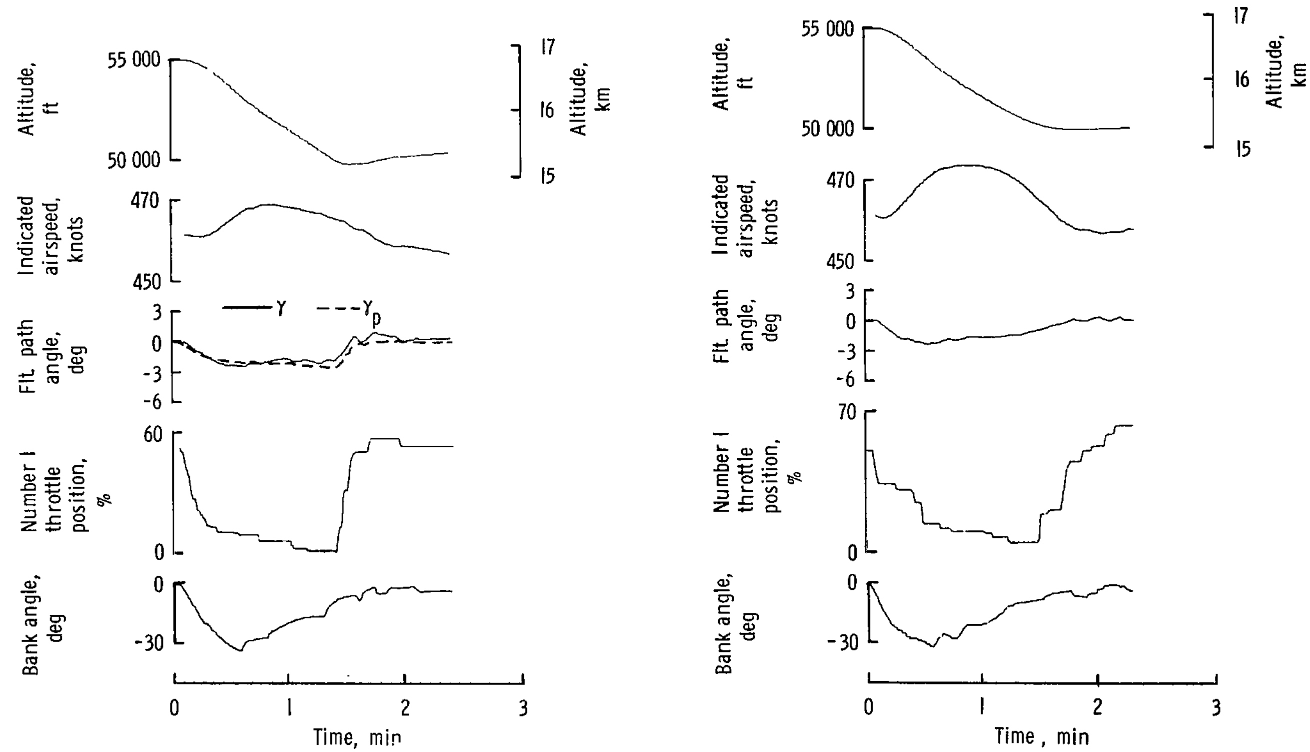
Figure 7.- Time histories of ILS intercept and descent both with and without $\dot{h}_p$ thrust-management instrument. Forward center-of-gravity location.



(a) With γ_p thrust-management instrument.

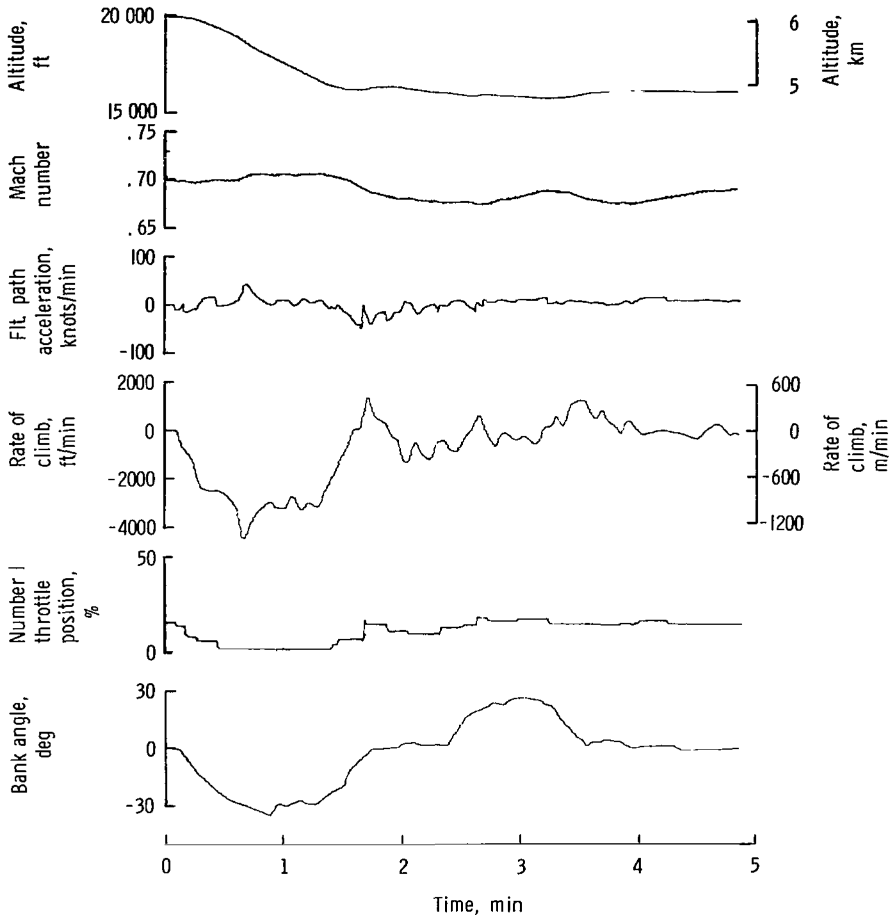
(b) Without γ_p thrust-management instrument.

Figure 8.- Time histories of constant indicated airspeed climbing turns at subsonic speeds both with and without γ_p thrust-management instrument. Forward center-of-gravity location.



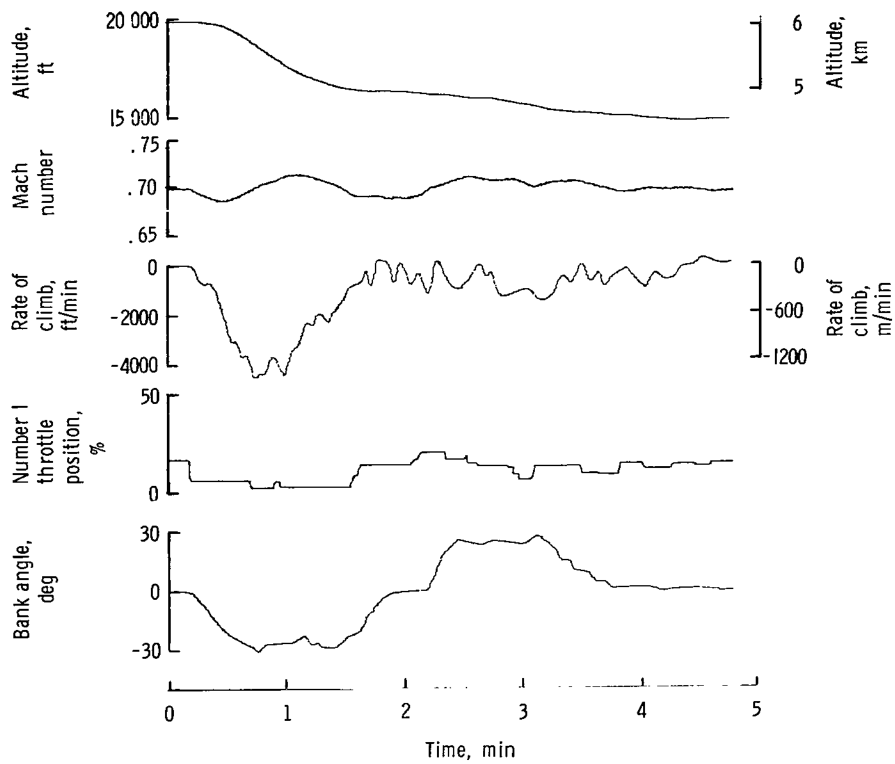
(a) With γ_p thrust-management instrument. (b) Without γ_p thrust-management instrument.

Figure 9.- Time histories of constant indicated airspeed descending turns of supersonic speeds both with and without γ_p thrust-management instrument. Forward center-of-gravity location.



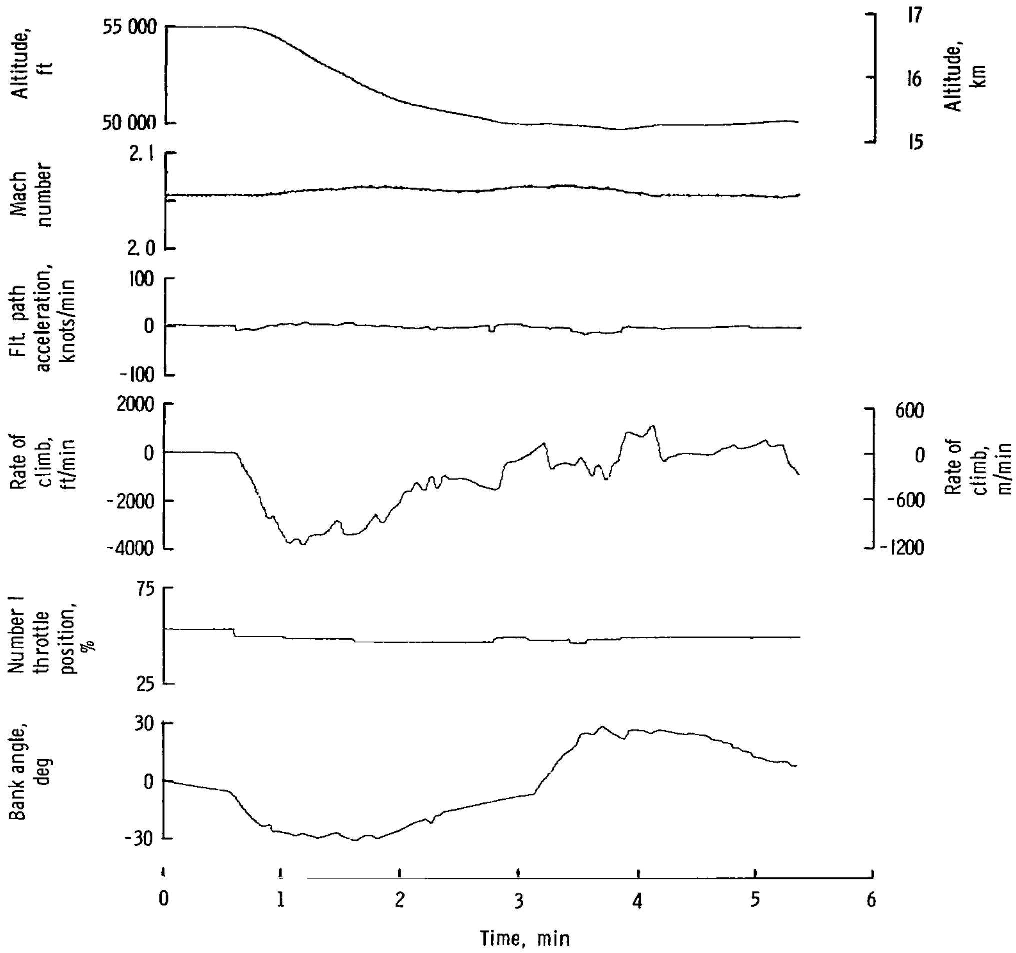
(a) With $\dot{V}$ thrust-management instrument (configuration B, table III).

Figure 10.- Time histories of constant Mach number descents and levels with turns at subsonic speeds both with and without $\dot{V}$ thrust-management instrument. Forward center-of-gravity location.



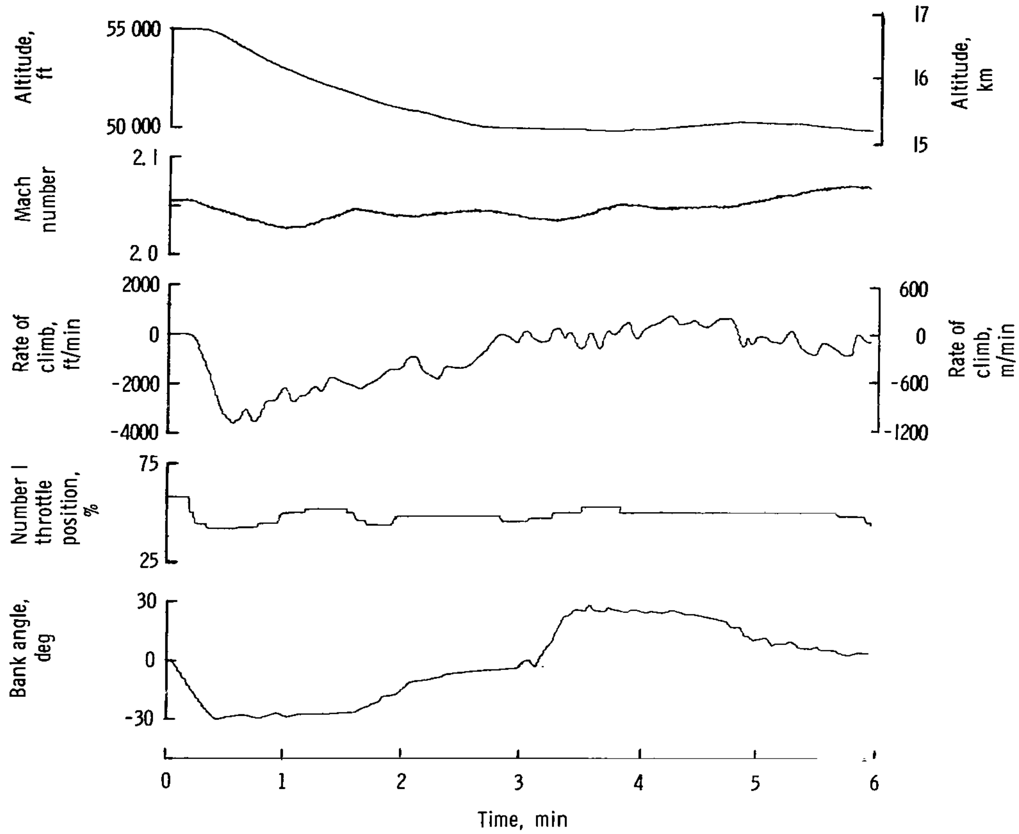
(b) Without $\dot{V}$ thrust-management instrument.

Figure 10.- Concluded.



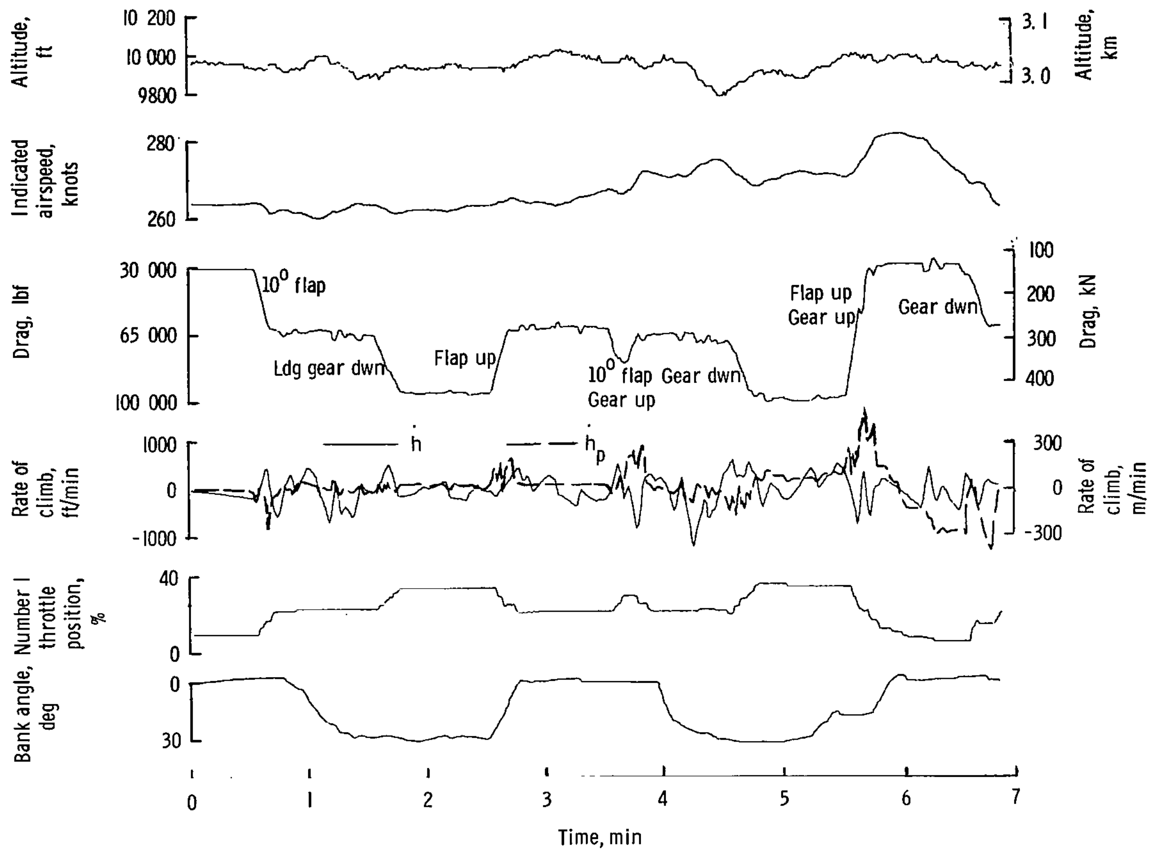
(a) With $\dot{V}$ thrust-management instrument (configuration B, table III).

Figure 11.- Time histories of constant Mach number descents and levels with turns at supersonic speeds both with and without the $\dot{V}$ thrust-management instrument. Forward center-of-gravity location.



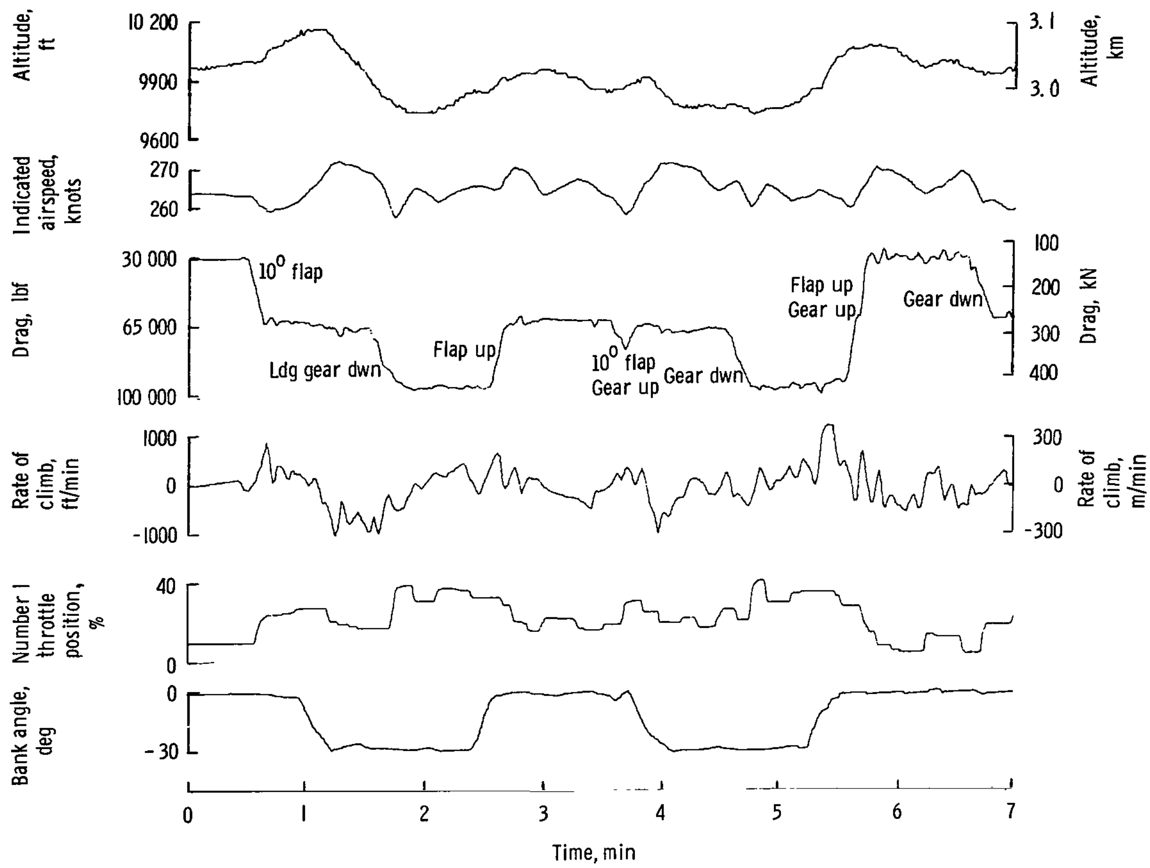
(b) Without $\dot{V}$ thrust-management instrument.

Figure 11.- Concluded.



(a) With $\dot{h}_p$ thrust-management instrument.

Figure 12.- Time histories of quantities measured as pilot attempted to apply thrust to trim drag changes both with and without a thrust-management instrument while following an oval flight pattern.



(b) Without $\dot{h}_p$ thrust-management instrument.

Figure 12.- Concluded.

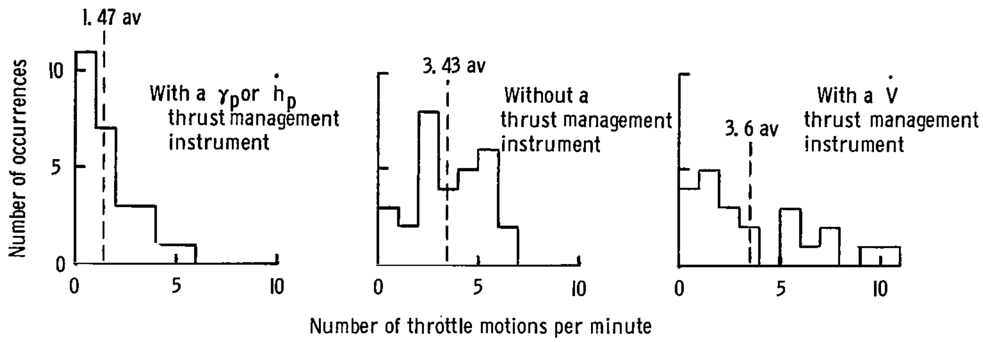


Figure 13.- Distribution of number of throttle motions per minute for tests with and without a thrust-management instrument.

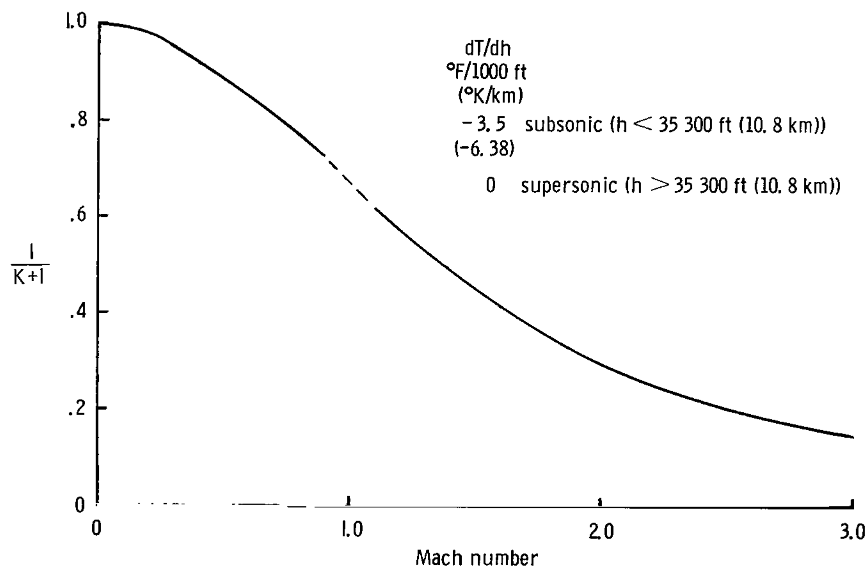


Figure 14.- Parameter $\frac{1}{K+1}$ plotted against Mach number for standard temperature variation with altitude.

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— NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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